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ANALYSIS OF SMOKE TRAIL PHOTOGRAPHS TO DETERMINE STRATOSPHERIC WINDS AND SHEARS

Air Force Geophysics Laboratory
Hanscom Air Force Base, Massachusetts

8 October 1976

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Analysis of Smoke Trail Photographs to Determine Stratospheric Winds and Shears

ANTONIO F. QUESADA
C. A. TROWBRIDGE

8 October 1976

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AERONOMY DIVISION PROJECT 6687
AIR FORCE GEOPHYSICS LABORATORY
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Time-lapse photographs of smoke trails deposited in the stratosphere have been measured and analyzed to provide data for the determination of winds and wind shears. Optimization techniques were required to define camera parameters with sufficiently high precision. In combination with a triangulation program that exploits the advantages of vector and matrix methods, the techniques lead to consistent three-station results that are used to construct wind profiles with an altitude resolution of 10 m.

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER:

John Howard

Chief Scientist

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1. INTRODUCTION

Detailed measurements of the vertical wind profile at stratospheric altitudes are required to evaluate atmospheric transport processes of importance in establishing dispersal rates of SST emissions. These rates are controlled by the intensity of turbulence and the local shear fields at spatial scales of the order of a few meters. Conventional balloon observations and meteorological rockets are not directed towards the definition of flow fields in the atmosphere at such small scales. To obtain the necessary high resolution, we have relied on observations and analysis of visible tracer trails deposited from rockets programmed to release a dense $TiCl_4$ smoke from the time the rocket reaches an altitude of some 15 km to apogee. The trails are photographed at regular intervals from at least two different locations to provide positional and timing information for triangulation, after which the wind field parameters and the shears are computed.

2. OPERATIONAL CONCEPT

To obtain the wind field parameters photogrammetric measurements are needed on photographs of successive positions of the trails laid by the rocket vehicle. For each field program, photographs were taken from three different sites at

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White Sands Missile Range. During February 1973, for example, measurements were made by triangulation cameras located at Doña Ana, "A" Mountain and Two Buttes. For the June 1973 and June 1975 programs, the sites selected were Two Buttes, Hotel and Seehorn. Figure 1 shows their locations as well at the location of the launching complexes. Coordinates of these stations are listed in Appendix A. At two of these sites three cameras were used. The third site had two cameras. In all cases a camera equipped with either a 20-in. or 7-in. focal length lens was co-mounted with a similar camera having a 7-in. lens. The field of view of the 20-in. lens was 12 × 12 deg and was adjusted to lie in the upper third of the field of the 7-in. camera which viewed a 36 × 36 deg field. At the sites where a third camera was used it carried a 7-in. lens and it was mounted on a separate rig oriented to photograph essentially the same field seen by the 7-in. co-mounted camera. The operation of the camera and film processing details are given in Appendix B. Figure 2 shows the evolution of a trail. The gaps are created intentionally to provide easily identifiable end points on views of the trail photographed from different sites. This procedure, introduced in 1975, facilitates the triangulation particularly after fine structure appears and the trail image has developed self intersections. As can be seen from Figure 2 the trail image becomes rather tangled in a surprisingly short time. Each of the triangulation photographs measures 12.5 × 12.5 cm and contains the trail image plus the images of fiducial marks that, together with the normal to the film plane, define a local Cartesian system of coordinates. The orientation of this local system with respect to some reference system (for example, horizon, geodetic, etc.) is determined by means of auxiliary photographs of the sky taken at known times during the night. Measurements of star image coordinates, referred to the film plane axes, are used for this purpose. If the cameras are not moved from the time the star background is photographed, a single transformation can be found to change the film plane coordinates into angular coordinates to identify the orientation of lines of sight to points on the trails.[1,2] If the cameras are moved, the coordinates of fixed objects that appear on photographs taken before and after the camera realighment (such as mountain tops or specially constructed targets) are needed to define additional transformation of coordinates. Computations have shown that in order to obtain a spatial resolution of the order of 10 m at a distance of some 30 km it is necessary to subject the trail photographs to a scanning operation on densitometric equipment capable of generating a raster with consecutive line separation of the order of 50 μ used in combination with scanning apertures approximately 50 μ square.

1. Quesada, A.F. (1971) AFCRL-71-0233, ERP No. 351.
2. Quesada, A.F. (1975) AFCRL-TR-75-0451, ERP No. 527.

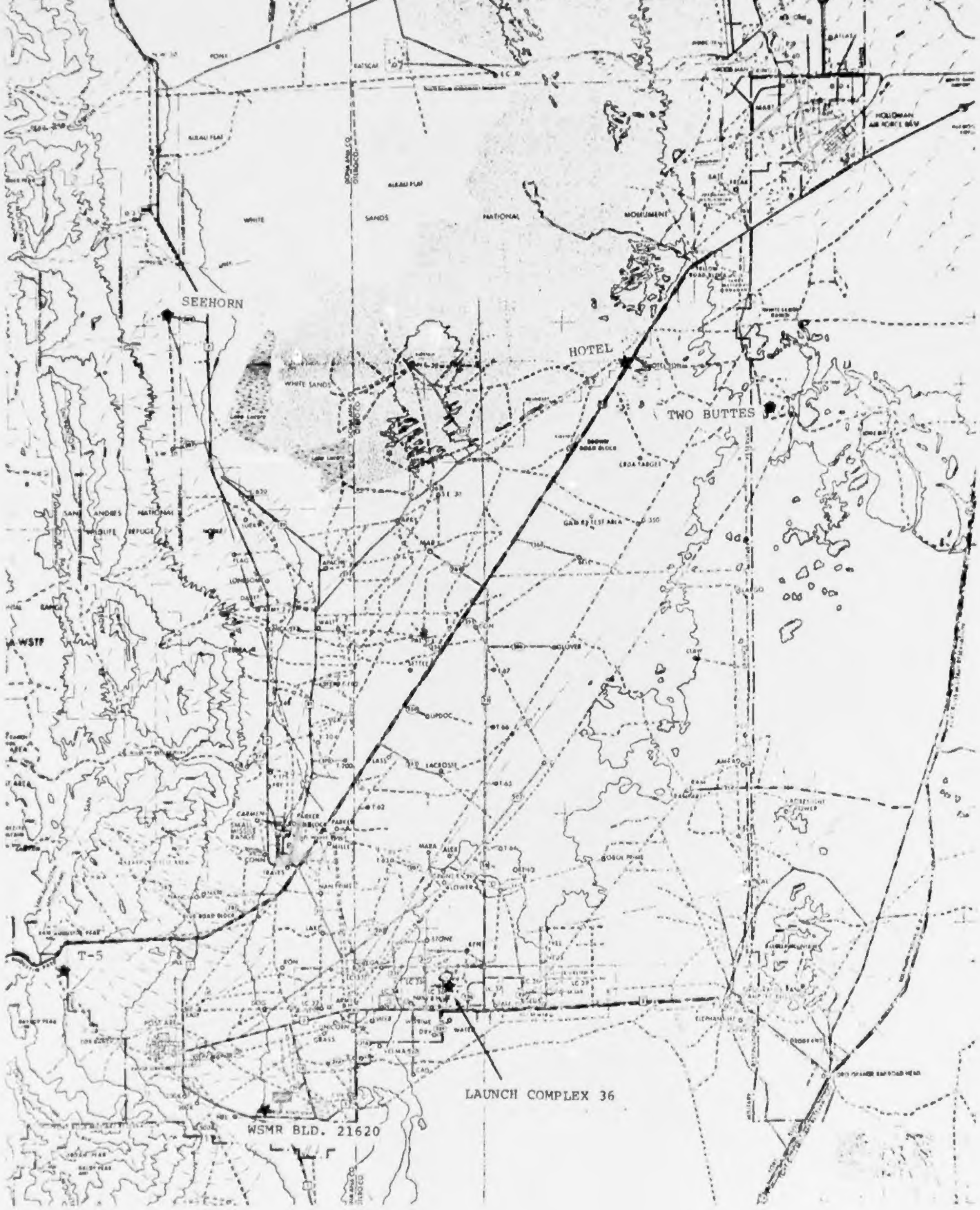

Figure 1. Location of Triangulation Sites

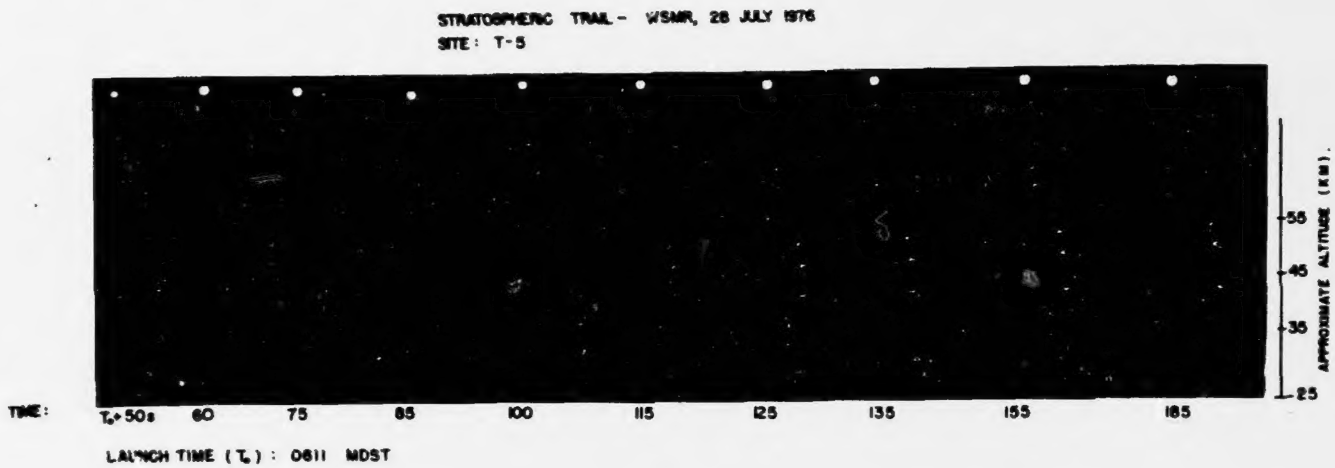

Figure 2. Evolution of Smoke Trail

Experience has shown that many trail sections can be scanned at half this resolution. Occasionally, there are film areas where the appearance of very fine detail requires a scan raster and aperture of 25 microns. In any event, the positional accuracy of the system must be such that x and coordinates of points along the trail are read with errors not exceeding one to two μ/centimeter. Appendix C describes a pictorial analysis facility (PAF) that meets these requirements. In order to preserve the high accuracy derived from scanning the trail photographs with the PAF equipment, the positional information is digitized and recorded on magnetic tape. The data on the tape, consisting of star coordinates, fiducial mark coordinates, trail coordinates and (possibly) auxiliary target coordinates, are processed on the CDC 6600 Computer at AFGL to determine the successive positions of points on the trails at altitude increments of 10 m. From three site positional data, wind velocities and error estimates are computed as functions of altitude and time.

3. TRIANGULATION PROCEDURE

The assignment of space coordinator to each point on the trail is a function of the orientation of the cameras and of the film-plane coordinates of each point. When the star calibration data are reduced, it is found that camera orientation parameters and camera focal length can be determined with errors measured by standard deviations of 0.01 to 0.03 deg and 0.01 cm, respectively.

The triangulation itself uses as a criterion for matching points on photographs of the trail corresponding to different sites the equality of dihedral angles formed by a line connecting a pair of observation sites and the line of sight vectors to a point on the trail. The triangulation package consists of a set of programs to implement the following procedures:

(1) Computation of camera focal length using star positions on the film plane,

(2) Determination of camera orientation from star positions,

(3) Determination of camera orientation from coordinates of auxiliary targets,

(4) Correction for atmospheric refraction when elevation angles are below 10 deg,

(5) Determination of coordinates of points along the trail from two-site positional data,

(6) Determination of statistics of point coordinates along the trail when three-site data are available,

(7) Conversion to coordinate systems more suitable to specify location of trails in space,

(8) Computation, tabulation and graphical displays of winds, wind shears and their errors.

Some of these programs are listed in Appendix D.

Figures 3 and 4 respectively, show the variation in the E-W and N-S components of the wind for one of the trails released during the June 1973 experiments, computed from two-site triangulation data.

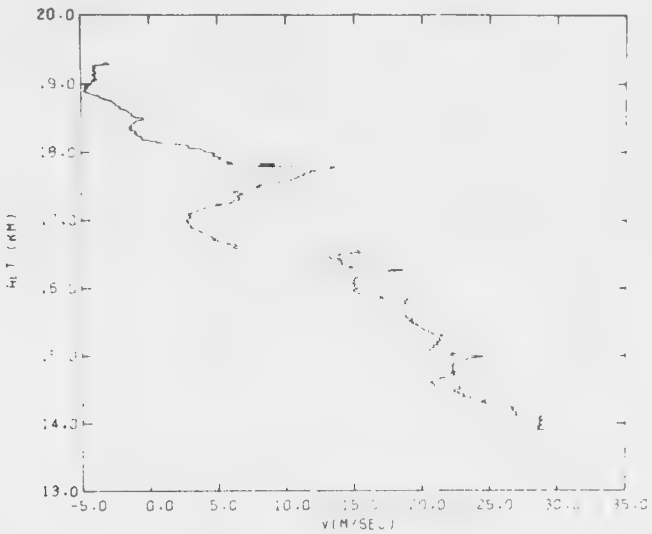

Figure 3. East-West Component of Wind Velocity

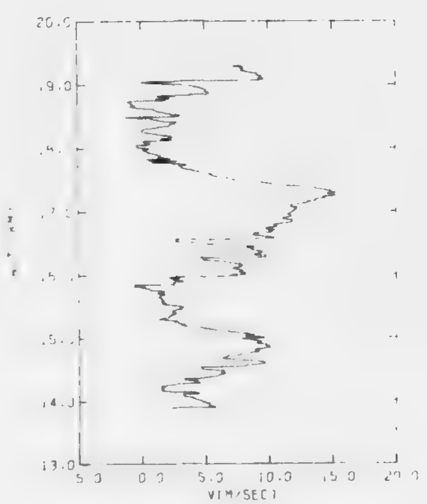

Figure 4. North-South Component of Wind Velocity

The early triangulation attempts and the subsequent calculation of winds and shears did not lead to satisfactory results. Lack of consistency was found in three areas:

(1) The position in space of a given point along the trail, obtained from data corresponding to a pair of sites, did not match the position of the same point when it was calculated from the data corresponding to a different pairing of sites. The ground plane discrepancies for some points were of the order of 50 to 200 meters.

(2) The wind profiles corresponding to different pairings did not agree, the discrepancies in this case being small shifts in the altitudes assigned to prominent features of the profile, and marked differences in the fine structure of the profiles.

(3) The shears showed abnormally high values at too many points in the altitude range that was covered.

An intensive search for possible causes for these discrepancies led to the conclusion that small changes in the orientation parameters of the camera and in the camera focal length were at fault. These changes are for the most part produced by agents not under the control of the operator. It was found, for example, that camera mounts can move slightly when the film magazines are taken on and off to protect the film against excessive heating during the day. They can also move when the canvas covers are put on or taken off. The focal length changes during the experiment due to heating of the cameras as the sun rises, etc. All of these factors can produce changes whose magnitude is a significant fraction of a standard deviation in the parameter values, that is, some tens of μ for the focal length and a few tenths of a mrad in the orientation parameters.

To apply corrections to the computed parameter values it is necessary to introduce an optimization procedure which, starting from the triangulated values of positions along the trail corresponding to a given paring of sites, computes the film plane coordinates of the trail for the site that is to be corrected and compares it with the original film plane coordinates that served as input data for the triangulation.

The program stop when the sum of the absolute values of the differences reaches a minimum. It ordinarily takes two or three iterations to zero in on a set of parameter values that bring positions computed from different pairings to better than 10 m (1 part in 5000) and makes the wind profiles coincide in all of the gross features and most of the fine structure. The shears are less pronounced and large values occur at very few altitudes.

Figure 5 shows the magnitude of the wind vs altitude computed from different site pairings for the June 1975 trail of Figures 3 and 4. Figure 6 displays the corresponding shears.

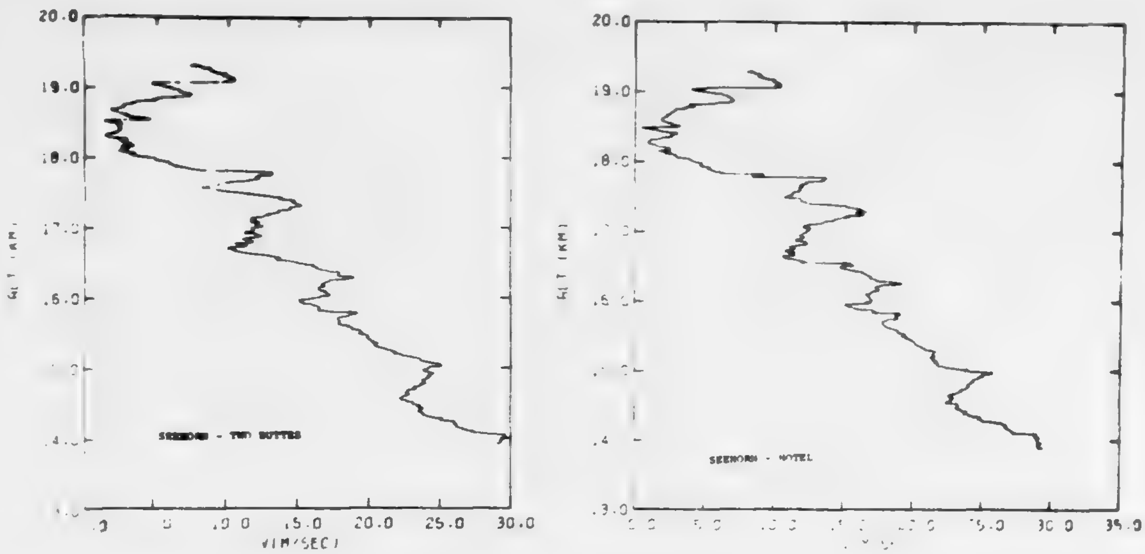

Figure 5. Magnitude of Wind Velocity Computed from Two Different Site Pairs

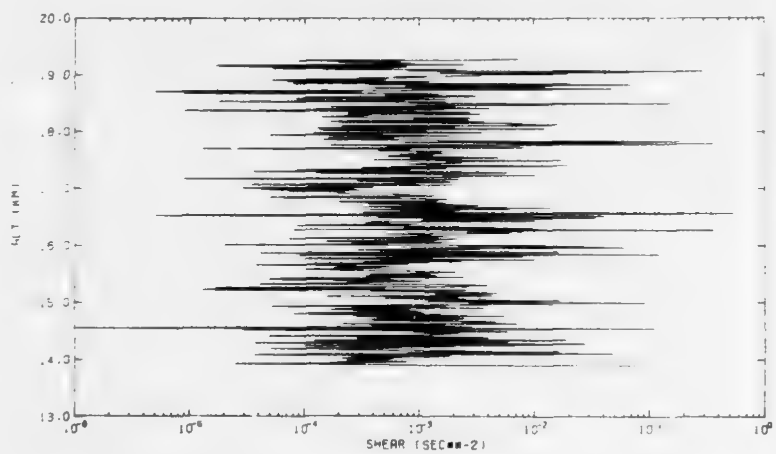

Figure 6. Profile of Wind Shear Squared

4. CONCLUSIONS

It has been established that stratospheric winds with a 10 m altitude resolution can be determined from time-lapse photographs of smoke trails. The orientation of the cameras is critical and must be measured with a precision that requires optimizing the focal length and the orientation parameters of the camera. When this

is done, the triangulation procedure applied to 3 or more sites leads to results that are consistent in assigning the space coordinates of points on the trail as well as to agreement of wind profiles in both, significant features and fine structure. Complementary optimization and triangulation are, therefore, a technique of data reduction which for the first time has made possible the computation of winds and shears with a resolution three times higher than has hitherto been reported.[3]

---

3. Miller, R.W., Henry, R.M., and Rowe, M.G. (1965) NASA TN D-2937.

Appendix A

Coordinates of Triangulation Sites

Station	Latitude*	Longitude*	Altitude**
Doña Ana	32° 08 ft 58.2340 in.	106° 30 ft 08.2121 in.	4.078.44 ft
"A" Mountain	32 17 17.2409	106 41 45.9135	4,754.0
Horn	32 44 24.1298	106 29 29.1790	4,425.42
Hotel	32 43 47.2904	106 12 50.7995	3,992.52
Two Buttes	32 42 12.8100	106 07 35.1100	4,555.6
Seehorn	32 45 20.747	106 29 12.164	4,343.7
T-5	32 25 19.0256	106 32 59.4567	5,404.8
WSMR (Bldg. 21620)	32 21 39.6309	106 24 32.4840	3,937.6
Holloman AFB (Bld. 1251)	32 55 27.0990	106 04 16.6859	4,185.2

* Geodetic Coordinates

** WSTM Coordinates

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Appendix B

Camera Operation and Film Development

Cameras

Modified K-46 aerial cameras were equipped with either 20-in. or 7-in. focal length lenses. Pairs of 20-in. and 7-in. or 7-in. and 7-in. cameras were arranged on a single mount for each site and rigidly locked to move as one unit with their optic axes offset in elevation by about 7 degrees. At two of the sites an additional 7-in. camera was mounted separately. Star calibrations were made, when the weather permitted, the night before the start of the experiments, and the night before each of the following launch sequences.* Exposure times of 15, 30, 60 and 120 sec were used. The elevation of the 7-in. cameras was chosen to allow full coverage of the trails and, in addition, show ground features or special targets near the bottom edge of the film. Daytime photography of the ground features was requested following the star calibrations. It is thus possible to correlate ground features and star calibrations to determine the camera orientation following possible changes in the camera azimuths. Azimuth adjustment during the experiments may be necessary to center the trail images within the field of view of the cameras. All cameras were provided with Polaroid filters mounted on top of Wratten 29 filters. The Polaroids were rotated shortly before launch until minimum sky brightness was observed.

---

*For the July 1976 experiments, a star calibration was made about 1 hr before the trail was released in order to minimize camera movements due to film magazine loading and unloading.

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Film Development

The negatives (Kodak 2402) were developed to have the following characteristics:

(1) Gamma in the range 1.2 to 1.5, determined from measurements of step wedge images exposed through a Wratten 29 filter and a Polaroid filter.

(2) Exposure for the sky background leading to a density on the negative approximately 0.3D above fog was desired. In case the exposure varied from the center to the edge of the field, the above criterion was to apply to the background density near the edges of the film, to provide reference lines for coordinate measurements in case the fiducial marks were lost.

(3) A developer was specified (D-76) that was compatible with the contrast requirements stipulated above and the fine grain to be expected from a film rated ASA 125.

Appendix C

Film Measurements

Film measurements are carried out under contract by Information Design, Inc. of Bedford, Massachusetts, using pictorial analysis equipment consisting of a photo scanner interfaced to a general purpose digital computer which also controls interactive display and recording peripheral units. Characteristics of this equipment are listed below.

(1) P-1000 computer controlled Photo Scanner with capability of scanning at any of the following X-Y rasters:

(a) 12.5 μ
(b) 25 μ
(c) 50 μ
(d) 100 μ
(e) 200 μ

Any of the following apertures can be used in combination with any of the above rasters:

(a) 12.5 μ^2
(b) 25 μ^2
(c) 50 μ^2
(d) 100 μ^2
(e) 200 μ^2
(f) 500 μ by 25 μ slit

Operation of the Photo Scanner is completely computer controlled.

X raster size, Y raster size, and the x and y boundary lines of the image area to be scanned are controlled by the software. Each aperture is centered at the intersections of the X-Y lattice raster.

(2) Alpha-16 general purpose digital computer interfaced to the P-1000.

(3) Proprietary interactive display interfaced to the computer.

The interactive display includes a cathode ray tube, keyboard and special digital knob controls. Using the knob controls, variables such as cursor positions or image brightness thresholds can be input to the computer program with 13-bit accuracy. The system provides the means for rapid and accurate manipulation of image data.

(4) Proprietary system control console that allows flexible interactive control and editing of data.

(5) Magnetic tape 800 b.p.i., 9 tracks, program for conversion to 7 track at 556 or 800 b.p.i.

(6) High speed paper tape reader and punch.

(7) General purpose computer software adapted to the above system configuration.

(8) High speed line printer.

The Pictorial Analysis Facility (PAF) has been programmed to detect and digitize the smoke trail images automatically. However, an operator can provide guidance via the display in order to initialize an image, track exceedingly thin trails and track self intersections of the trail image. Positional x, y accuracy of the densitometer is specified by the manufacturer as 1 μ rms/cm.

Each frame is scanned perpendicular to the direction of smoke trail ascent. Thus, scan lines generally cross the smoke trail images at approximately right angles. The array of optical density measurements for each scan line is analyzed automatically by computer program to find the excursion caused by the smoke trail image.

The operator monitors the digitization of the initial frame of each sequence. After these are digitized, the computer retains an abbreviated model of the n-1 frame smoke trail image. This model consists of smoke trail image x, y-coordinates spaced at 1 mm distances along the vertical dimension of the trail image.

When the nth frame is digitized, frame-to-frame correlation is used to direct the scanner to the appropriate location of the film. The search for the trail on the nth frame is centered on the location of the trail on the n-1 frame.

In addition, scan-line to line-scan correlation is used to compare x, y coordinate locations for the n-1 and nth scan lines in any frame. Using information both from the previous scan line on the same frame and from the same scan line on the previous frame provides a good set of expected coordinates for the current scan line. Initially the operator may define a band of allowable deviation from these

coordinates, or the program may use preset values. PAF scans each smoke trail automatically until an out-of-tolerance coordinate pair is detected and then summons the operator to interactively guide the scanning process. If necessary, the operator may direct the PAF to repeat the last few scan lines. The excursion in optical density values caused by the smoke trail images is analyzed by computer to determine the center of the image for each scan line. The results of this analysis are smoke trail coordinates ready for storage on magnetic tape.

Trail image thickness are calculated each time an x, y coordinate pair is detected. Trail image thickness of less than a preselected threshold causes the computer to summon the operator for supervision and interactive guidance.

At this point, the computer displays an image of the area surrounding the anticipated location of the smoke trail image or an area designated by the operator. The operator guides the digitization by viewing a cross section of the optical density profile for the smoke trail image, and moving a cursor to designate the position of the smoke trail. When the trail widens beyond the threshold, the PAF notifies the operator that it has returned to the automatic mode of operation.

All fiducial mark, star, auxiliary target and smoke trail coordinates as required are stored on magnetic tape fully compatible with the CDC 6600 computer system currently in use at AFGL.

Appendix D

Computer Programs

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```
      PROGRAM TRIANG(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,
     1TAPE20,TAPE1=150,TAPE2=150,TAPE11=150,TAPE12=150,TAPE3)
C
C     THIS PROGRAM TRIANGULATES A TRAIL RELEASE, AND CALCULATES THE
C     GEOCENTRIC AND GEODETIC COORDINATES.
C     THE LIMITS ON THIS PROGRAM ARE, 3 SITES, AND 3000 POINTS PER SITE.
C
      REAL IDENT
      DIMENSION XX(3000),YY(3000)
      COMMON C(3,3000),IDENT(7,4),N(3),RHO(3,3),D(3),
     1AV2(3),DU(3),FL(3),AZIM(3),AEL(3),DELTAE(3),
     2TITLE(8,3),XI(4),YI(4),ID(4),
     3TEMP1(3),TEMP2(3),TEMP3(3),CC(3),AV(3)
     4,GH(3),ACEN(3),DEC(3)
      PI=3.14159265358979
      RAD=180./PI
      J=1
      REWIND 20
      REWIND 1
      REWIND 2
      REWIND 3
      READ(5,350) NT1
  350 FORMAT(I3)
      WRITE(6,10)
   10 FORMAT (1H1)
      DO 300 NT=1,NT1
      REWIND 11
      REWIND 12
      J=1
   65 IUNIT=10+J
C
C     READ THE SITE NAME, AND ITS GEODETIC COORDINATES. (LAT,LON)
C
      READ(5,30)(IDENT(I,J),I=1,2),IDENT(3,J),IDENT(4,J),IDENT(7,J)
   30 FORMAT(2A10,2F10.4,F10.5)
      IF(IDENT(1,J).EQ.10H          ) GO TO 200
      IDENT(3,J)=IDENT(3,J)/RAD
      IDENT(4,J)=IDENT(4,J)/RAD
      TEMP1(1)=IDENT(3,J)*RAD
      TEMP1(2)=IDENT(4,J)*RAD
      PRINT 50,(IDENT(I,J),I=1,2),TEMP1(1),TEMP1(2),IDENT(7,J)
   50 FORMAT(// ,58X,2A10,F10.4,*N. LAT.*F10.4*W. LONG.*/
     1 56X,F7.2*METERS*)
C
C     CONVERT GEODETIC TO GEOCENTRIC COORDINATES.
C
      CALL CONVRT(1,IDENT(3,J),IDENT(4,J),IDENT(7,J)/1000.,IDENT(5,J),
     1IDENT(6,J),RHO(1,J))
C
C     READ THE UNIVERSAL TIME AND DATE.
C
      READ(5,120) JHR,JMIN,SEC,MO,IDAY,IYR
  120 FORMAT (2I3,F7.0,7X,I2,2I3)
      UT=(JHR+(JMIN+SEC/60.)/60.)/24.
C
C     CALCULATE SIDERIAL TIME.
C
```

```
C
      CALL JULDAY(JDAY,IYR,MJ,IDAY)
      TU=(JDAY+0.5+UT-2415020.)/36525.
      RU=18.+(38.+45.836/60.)/60.+(8640184.542*TU+0.0929*TU*TU)/3600.
      RUU=AMOD(RU,24.)
      GHA=(12.+UT*24.+RUU)/24.*2.0*PI
      IF(GHA.GE.2.0*PI) GHA=GHA-2.0*PI
C
C     READ THE CAMERA FOCAL LENGTH IN CM.
C
      READ(5,20) FL(J)
      WRITE( ,110) FL(J)
  110 FORMAT (5X,*FOCAL LENGTH =*F7.3* CM*,/)
C
C     READ CONSTANTS WHICH DEFINE THE CAMERA ORIENTATION.(IN DEGREES)
C
      READ(5,20) AZIMM,ELEV,DELTAE(J)
      PRINT 560
  560 FORMAT(1X,*   AZ         EL           TILT*)
      PRINT 20,AZIMM,ELEV,DELTAE(J)
      AV(1)=AV(2)=0.
      AV(3)=1.
      AZIMM=AZIMM/RAD     $ELEV=ELEV/RAD
      CALL ROT(AV,AV,PI/2.-ELEV,1)
      CALL ROT(AV,AV,AZIMM,3)
      CALL ROT(AV,AV,-PI/2.+IDENT(5,J),1)
      DECL=ASIN(AV(3))
      ASENC=ATAN2(AV(1),AV(2))
      ASENC=PI-IDENT(6,J)+GHA-ASENC
      ASENC=AMOD(ASENC,2.*PI)
      ASCENC=ASENC*RAD    $DECLC=DECL*RAD
      DELTAE(J)=DELTAE(J)/RAD
   20 FORMAT (3F10.5)
      AV(1)=AV(2)=0.
      AV(3)=1.
      CALL ROT(AV,AV,PI/2.-ELEV,1)
      CALL ROT(AV,AV,PI/2.+AZIMM-DELTAE(J),3)
      ASC=ATAN2(AV(1),-AV(2))
      DELTAE(J)=ASC*RAD
      TEMP1(1)=ASCENC
      TEMP1(2)=DECLC
      TEMP1(3)=DELTAE(J)
      ASCENC=ASCENC/RAD
      DECLC=DECLC/RAD
      DELTAE(J)=DELTAE(J)/RAD
      GH(J)=GHA
      IF(J.EQ.2.AND.GH(1).EQ.GH(2)) GO TO 69
      IF(J.EQ.1) GO TO 69
      DLGH=GH(1)-GH(2)
      GH(2)=GH(1)
      GHA=GH(1)
      ASCENC=ASCENC-DLGH
      TEMP1(1)=ASCENC*RAD
   69 ACEN(J)=ASCENC
      DEC(J)=DECLC
C
C     CALCULATE THE AZIMUTH AND ELEVATION OF THE COF OF THE CAMERA.
```

```
      C
            AV(1)=0.0
            AV(2)=0.0
            AV(3)=1.0
            CALL ROT(AV,AV,-PI/2.+DECLC,2)
            CALL ROT(AV,AV,GHA-ASCENC-IDENT(6,J),3)
            CALL ROT(AV,AV,PI/2.-IDENT(5,J),2)
            AEL(J)=ASIN(AV(3))
            AAEL=AEL(J)*RAD
            AZIM(J)=ATAN2(AV(2),-AV(1))
            AAZIM=AZIM(J)*RAD
            WRITE(6,70) (TEMP1(I),I=1,3),AAZIM,AAEL,GHA
         70 FORMAT (  /,40X,*RIGHT ASCENSION OF CAMERA =*F08.3,/,
           140X,*DECLINATION OF CAMERA =*F08.3,/,
           240X,*ROTATION OF THE FILM PLANE =*F08.3,/,
           4///,T24,*AZIMUTH =*F8.3,T54,*ELEVATION =*F7.3,T84*SIDEREAL TIME =*
           5F6.3)
      C
      C     READ THE HEADER CARD.
      C
            READ(J,111) (TITLE(I,J),I=1,8)
        111 FORMAT (8A10)
            WRITE(6,121) (TITLE(I,J),I=1,8)
        121 FORMAT (/,30X,8A10)
            K=1
      C
      C     READ THE X AND Y COORDINATES OF THE POINT RELEASES IN THE
      C     FILM PLANE, AND CALCULATE THE LINE OF SIGHT.
      C
            LL=0
        125 READ(J,131) (XI(L),YI(L),IP(L),L=1,4)
            LL=LL+1
        131 FORMAT(1X,4(2F8.4,I4))
            IF(EOF (J)) 180,135
        135 DO 171 L=1,4
            IF(XI(L).EQ.0.0.AND.YI(L).EQ.0.0) GO TO 171
            XI(L)=-XI(L)
            XX(K)= XI(L)
            YY(K)=YI(L)
            CALL ANGLE(FL(J)    ,XI(L),YI(L),SIGMA,ETA)
            CALL LINSGT(SIGMA,ETA,ASCENC,DECLC,DELTAE(J),GHA,
           1C(1,K),C(2,K),C(3,K))
      C
      C     THESE STATEMENTS ARE USED ONLY WHEN A COMPLETE PRINTOUT IS DESIRED
      C
            GO TO 55
            AV(1)=COS(ETA)*SIN(SIGMA)
            AV(2)=SIN(ETA)*SIN(SIGMA)
            AV(3)=COS(SIGMA)
            CALL ROT(AV,AV,-DELTAE(J),3)
            CALL ROT(AV,AV,-PI/2.+DECLC,2)
            CALL ROT(AV,AV,GHA-ASCENC-IDENT(6,J),3)
            CALL ROT(AV,AV,PI/2.-IDENT(5,J),2)
            AAEL=ASIN(AV(3))*RAD
            AAZIM=ATAN2(AV(2),-AV(1))*RAD
            SIGMA=SIGMA*RAD
            ETA=ETA*RAD
```

```
      WRITE(6,161) ID(L),XI(L),YI(L),SIGMA,ETA,AAZIM,AAEL,(C(I),I=1,3)
  161 FORMAT(5X,I5,3F10.5,F12.5,2X,2F7.2,3F10.5,3X,F7.3,5X,F7.3)
   55 K=K+1
  171 CONTINUE
      GO TO 125
  180 N(J)=K-1
      WRITE(6,80) N(J)
   80 FORMAT (/,T54,I4,* NPTS*)
      K=N(J)
      WRITE(IUNIT,60) (XX(JJ),YY(JJ),(C(II,JJ),II=1,3),
     1JJ=1,K)
   60 FORMAT (2F8.4,3F12.8)
      J=J+1
      ENDFILE IUNIT
      REWIND IUNIT
      IF(J.EQ.3) GO TO 200
      GOTO 65
  200 CONTINUE
      WRITE(6,10)
      WRITE(6,40)
   40 FORMAT(1HT)
      JSTA=J-1
      KKSUM=0
      SUMX=0.
      SUMX2=0.
      SYD=SYD2=0.
      KPLUS=0
      KMIN=0
C
C     WRITE THE HEADING OF THE DATA FILES, AND REWIND THE FILES.
C
      DO 51 I=1,JSTA
      IF(I.EQ.2) GO TO 51
      DO 41 J=1,JSTA
      IF(J.EQ.I) GO TO 41
      WRITE(20,225) SEC
  225 FORMAT(1X,F7.0)
      WRITE(6,121) (TITLE(L,I),L=1,8)
      WRITE(6,121) (TITLE(L,J),L=1,8)
      WRITE(20,111) (TITLE(L,I),L=1,8)
      WRITE(20,111) (TITLE(L,J),L=1,8)
      WRITE(3,111)(TITLE(L,J),L=1,8)
      IUNIT=10+I
      JUNIT=10+J
      REWIND IUNIT
      REWIND JUNIT
      NN=N(J)
      NNI=N(I)
      READ(JUNIT,60) (XX(JJ),YY(JJ),(C(II,JJ),II=1,3),JJ=1,NN)
      CALL VECTOR(RHO(1,I),RHO(1,J),D,2)
      CALL SCALCF(D,D,ZZ,2)
      ZZ=1./SQRT(ZZ)
      CALL SCALCF(D,DU,ZZ,1)
      IFR=0
      JTT=1
      INIT=0
      JT=JTT
```

```
      JTSAV=1
C
C     CALCULATE THE INTERSECTION OF THE LINE OF SIGHT AND THE TRAIL
C     AS SEEN FROM ANOTHER SITE.
C
      STCOM=500
      DO 299 KK=1  ,NNI
      READ(IUNIT,60) X,Y,(CC(II),II=1,3)
   47 DO 220 L=1,3
      TEMP1(L)=CC(L)
  220 CONTINUE
C
C     CALCULATE THE INTERSECTION OF TWO LINES OF SIGHT.
C
      ISW=0
      IC=0
      ISW1=0
      ICOM=3
      FMIN=1.E+7
      FCOMP=2.E-8
      ZCOMP=.002
      ZMIN=100.
      JT=JTSAV
      IF(JT.LT.1) JT=1
  221 CALL SCALCF(D,C(1,JT),TEMP2(1),2)
      CALL SCALCF(D,TEMP1(1),TEMP2(2),2)
      CALL SCALCF(TEMP1(1),C(1,JT),TEMP2(3),2)
      AA=1.0-TEMP2(3)*TEMP2(3)
      SLR=(TEMP2(1)-TEMP2(2)*TEMP2(3))/AA
      SLRI=-(TEMP2(2)-TEMP2(1)*TEMP2(3))/AA
C
C     CALCULATE ERROR VECTOR
C
      CALL SCALCF(C(1,JT),TEMP2(1),SLR,1)
      CALL VECTOR(D,TEMP2(1),TEMP2(1),2)
      CALL SCALCF(TEMP1(1),TEMP3(1),SLRI,1)
      CALL VECTOR(TEMP2(1),TEMP3(1),TEMP3(1),1)
      CALL SCALCF(TEMP3(1),TEMP3(1),AA,2)
      CALL VECTOR(DU,TEMP1,AV,3)
      CALL VECTOR(DU,C(1,JT),AV2,3)
      CALL SCALCF(AV,AV,XXX,2)
      CALL SCALCF(AV2,AV2,YYY,2)
      XXX=1./SQRT(XXX)
      YYY=1./SQRT(YYY)
      CALL SCALCF(AV,AV,XXX,1)
      CALL SCALCF(AV2,AV2,YYY,1)
      CALL SCALCF(AV,AV2,F,2)
      F=1.-ABS(F)
      ZZ=SQRT(AA)
      IF(ISW.EQ.1) GO TO 260
      IC=IC+1
      IF(ISW1.EQ.0) GO TO 228
      IF(F.LE.FCOMP.AND.ZZ.LT.ZMIN) GO TO 228
      GO TO 229
  228 JTMIN=JT
      FMIN=F
      ZMIN=ZZ
```

```
      ISW=1
  229 IF(ICOM.GT.STCOM) GO TO 240
      IF(FMIN.LE.FCOMP.AND.ZMIN.LE.ZCOMP) GO TO 240
      IF(IC.GT.ICOM) GO TO 231
  232 JT=JT+1
      IF(JT.GT.NN) GO TO 240
      GO TO 221
  230 FORMAT(*  NO SATISFACTORY MATCH AFTER*I3* ATTEMPTS*)
  231 CONTINUE
  239 ICOM=ICOM+1
      GO TO 232
  240 JT=JTMIN
      ISW=1
      IF(ZMIN.LT.0.005.AND.FMIN.LT.FCOMP*5.) GO TO 221
      WRITE(6,230) IC
      GO TO 299
  260 CALL FPPOS(CC,SLRI,RHO,ACEN,DEC,DELTAE,
     1 GH,FL,XV,YV)
      STCOM=30
      YMIN=SQRT((XV-XX(JT))**2+(YV-YY(JT))**2)
      ZZ=ZZ*1000.
      F=F*1000000.
      SYD=SYD+YV-YY(JT)
      SYD2=SYD2+YMIN
C NEXT CARD FOR SITE 2 FILM PLANE PLOT
      WRITE(3,265) XV,YV,KK
  265 FORMAT(1X,2E11.4,I4)
      JTSAV=JT
      JTT=ZZ
      CALL SCALCF(C(1,JT),TEMP1,SLR,1)
      CALL VECTOR(RHC(1,J),TEMP1,AV,1)
      ZZ=0.5
      CALL SCALCF(TEMP3(1),TEMP3(1),ZZ,1)
      CALL VECTOR(AV,TEMP3(1),TEMP2,1)
C
C     CONVERT TO LAT, LONG, AND ALT.
C
      AA=ASIN(TEMP2(3)/SQRT(TEMP2(1)**2+TEMP2(2)**2+TEMP2(3)**2))
      BB=ATAN2(TEMP2(2),TEMP2(1))
      CALL CONVRT(2,TEMP1(1),TEMP1(2),TEMP1(3),AA,BB,TEMP2(1))
      TEMP1(1)=TEMP1(1)*RAD
      TEMP1(2)=TEMP1(2)*RAD
      WRITE(6,290) KK,I,J,YMIN,(TEMP1(II),II=1,3),SLR,SLRI,F,IC,JT,JTT
  290 FORMAT(9X,I4,1X,2I3,1X,F8.5,1X,F12.5,F18.5,F17.3,5X,F10.4,4X,F10.4
     1,1X,F10.3,I3,I5,I5)
      WRITE(20,320)(TEMP1(II),II=1,3)
  320 FORMAT(1X,3F10.5)
      KKSUM=KKSUM+1
      IF(KKSUM.EQ.1) GO TO 297
      VAR=TEMP1(3)-ZLAST
      IF(VAR.LE.0.) KMIN=KMIN+1
      IF(VAR.GT.0.) KPLUS=KPLUS+1
      SUMX=SUMX+VAR
      SUMX2=SUMX2+VAR**2
  297 ZLAST=TEMP1(3)
  299 CONTINUE
 2395 ENDFILE 20
```

```
   41 CONTINUE
   51 CONTINUE
      FS=KKSUM
      AB=SUMX/FS
      ASIG=SQRT(KKSUM*SUMX2-SUMX*SUMX)/FS
      SYD2=(SYD2/FS)
      SYD=SYD/FS
      PRINT 305,AB,ASIG,KKSUM,KMIN,KPLUS,SYD2,SYD
      WRITE(6,10)
  305 FORMAT(1H0,*AVERAGE ALTITUDE INCREMENT = *F8.4/
     1 * SIGMA = *F11.6/* TOTAL MATCHES = *I6/
     2 * NO. ALTITUDE DECREASES = *I6/
     3 * NO. ALTITUDE INCREASES = *I6/
     4 * ABS Y DEVIATION SITE 2 = *F12.7/
     5 * AV Y DEVIATION SITE2 = *F12.7)
      END FILE 3
  300 CONTINUE
  310 CONTINUE
      STOP
      END
```

```
      SUBROUTINE ORIENT(V,ASCENC,DECLC,DELTAE)
C
C     THIS SUBROUTINE CALCULATES THE ORIENTATION OF THE CAMERA
C     FROM THE POSITION OF A PAIR OF STARS. (ALL ANGLES ARE IN RADIANS)
C
      DIMENSION V(3,4),VD(3,2),B(3)
      IFLAG=0
      PI=3.14159265
C
C     CALCULATE DIFFERENCES,
C
      DO 11 I=1,2
      CALL VECTOR(V(1,I),V(1,2+I),VD(1,I),2)
   11 CONTINUE
C
C     CALCULATE AND SCALE B.
C
      CALL VECTOR(VD(1,1),VD(1,2),B,3)
      CALL SCALCF(B,B,C,2)
      C=SQRT(C)
      CALL SCALCF(B,B,1./C,1)
C
C     CALCULATE ROTATION ANGLE.
C
   15 CALL SCALCF(V(1,1),V(1,3),C,2)
      CALL SCALCF(V(1,1),B,D,2)
      D=D*D
      COMEGA=(C-D)/(1.0-D)
      SOMEGA=SQRT(1.0-COMEGA**2)
      OMEGA=ATAN2(SOMEGA,COMEGA)
C
C     CALCULATE ASCENC,DECLC AND DELTAE.
C
      T1=ATAN2(B(1),B(2))
      T2=SIN(OMEGA/2.0)/COS(OMEGA/2.0)
      T3=ATAN(B(3)*T2)
      ASCENC=T3-T1
      DELTAE=T3+T1
      T1=COMEGA+(1.-COMEGA)*B(3)*B(3)
      T2=SQRT(1.-T1*T1)
      DECLC =ATAN2(T1,T2)
      IF(IFLAG.EQ.0) GO TO 25
      RETURN
   25 CALL VECTOR(V(1,3),B,VD(1,2),3)
      CALL SCALCF(VD(1,2),VD(1,1),SIN(OMEGA),1)
      CALL SCALCF(V(1,3),B,C,2)
      C=C*(1.-COS(OMEGA))
      CALL SCALCF(B,VD(1,2),C,1)
      CALL VECTOR(VD(1,1),VD(1,2),VD(1,1),1)
      CALL SCALCF(V(1,3),VD(1,2),COS(OMEGA),1)
      CALL VECTOR(VD(1,1),VD(1,2),VD(1,1),1)
      DO 31 J=1,3
      IF(ABS(VD(J,1)-V(J,1)).GT.0.050) GO TO 5
   31 CONTINUE
      RETURN
    5 DO 21 I=1,3
      B(I)=-B(I)
   21 CONTINUE
      IFLAG=1
      GO TO 15
      END
```

```
      SUBROUTINE CONVRT(K,GDLAT,GDLON,H,GCLAT,GCLON,RHO)
C
C     THIS SUBROUTINE CONVERTS GEODETIC COORDINATES TO GEOCENTRIC
C     COORDINATES WHEN K=1. (ALL ANGLES ARE IN RADIANS)
C
C     WHEN K=2, THE INVERSE TRANSFORMATION OCCURS.
C
      DIMENSION RHO(3)
C
C     CLARKE'S ELLIPSOID OF 1866 IS USED.
C
      RA=6378.2064
      RB=6356.5838
      RR=(RB/RA)**2
      EC=1.-RR
C
C     SELECT OPTION.
C
      GO TO(5,15),K
C
C     CONVERT GEODETIC TO GEOCENTRIC COORDINATES.
C
    5 GCLON=GDLON
      C=RA/(SQRT(1.0-EC*(SIN(GDLAT))**2))
      GCLAT=ATAN((RR+H/C)/(1.+H/C)*TAN(GDLAT))
      RHO(1)=(C+H)*COS(GDLAT)*COS(GDLON)
      RHO(2)=-(C+H)*COS(GDLAT)*SIN(GDLON)
      RHO(3)=(C*RR+H)*SIN(GDLAT)
      RETURN
C
C     CONVERT GEOCENTRIC TO GEODETIC COORDINATES.
C
   15 IF(GCLON.LT.0.0) GCLON=-GCLON
      GDLON=GCLON
      C=RA/SQRT(RHO(1)*RHO(1)+RHO(2)*RHO(2)+RHO(3)*RHO(3))
      T=ATAN(SQRT(RR)*(TAN(GCLAT)+C*EC*TAN(GCLAT)/SQRT(1.-EC*(SIN(GCLAT)
     1)**2)+.5*C*C*EC*EC*SIN(2.*GCLAT)/(1.-EC*SIN(GCLAT)**2)))
      C=RA/C
      H=SQRT(C*C-2.*RA*C*(COS(GCLAT)*COS(T)+SQRT(RR)*SIN(GCLAT)*SIN(T))+
     1RA*RA*(1.-EC*(SIN(T)**2)))
      GDLAT=ATAN((C*SIN(GCLAT)-RA*SQRT(RR)*SIN(T))/(C*COS(GCLAT)-
     1RA*COS(T)))
      RETURN
      END
```

```
      SUBROUTINE ANGLE(FL,X,Y,SIGMA,ETA)
C     THIS SUBROUTINE CALCULATES THE ANGLES WHICH DEFINE A POINT
C
C     IN THE FILM PLANE. (ANGLES ARE EXPRESSED IN RADIANS)
C
      D=SQRT(X*X+Y*Y)
      SIGMA=ATAN(D/FL)
      ETA=ATAN2(Y,X)
    5 RETURN
      END
```

```
      SUBROUTINE LINSGT(SIGMA,ETA,ASCENC,DECLC,DELTAE ,TAU,X,Y,Z)
C
C     PERFORM THE REQUIRED ROTATIONS TO DETERMINE THE LINE OF SIGHT
C
      DIMENSION V(3)
      PI=3.14159265358979
      V(3)=SIN(SIGMA)
      V(1)=COS(ETA)*V(3)
      V(2)=SIN(ETA)*V(3)
      V(3)=COS(SIGMA)
C
C     ROTATE ABOUT THE Z AXIS.
C
      ANG=-DELTAE
      CALL ROT(V,V,ANG,3)
C
C     ROTATE ABOUT Y AXIS.
C
      ANG=-PI/2.0+DECLC
      CALL ROT(V,V,ANG,2)
C
C     ROTATE ABOUT Z AXIS.
C
      ANG=TAU-ASCENC
      CALL ROT(V,V,ANG,3)
      X=V(1)
      Y=V(2)
      Z=V(3)
      RETURN
      END
```

```
      SUBROUTINE SCALCF(X1,X2,S,NOP)
C
C     THIS SUBROUTINE MULTIPLIES A VECTOR X1 BY A SCALAR S WHEN NOP=1,
C     AND PLACES THE RESULTS IN X2.
C     IF NOP=2, THE DOT PRODUCT OF VECTORS X1 AND X2 IS STORED IN S.
C
      DIMENSION X1(1),X2(1)
      IF(NOP.GT.2)WRITE(6,5)NOP
    5 FORMAT(1X,* AT SCALCF, NOP=*,I10)
      GO TO(1,3),NOP
    1 DO 2 J=1,3
      X2(J)=S*X1(J)
    2 CONTINUE
      RETURN
    3 S=0.
      DO 4 J=1,3
      S=S+X1(J)*X2(J)
    4 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE VECTOR(X1,X2,X3,NOP)
C
C     THIS SUBROUTINE PERFORMS VECTOR ADDITION IF NOP=1,VECTOR
C     SUBTRACTION IF NOP=2, AND CALCULATES THE VECTOR PRODUCT IF
C     NOP=3.  X1 AND X2 ARE THE INPUT VECTORS AND X3 IS THE RESULTANT
C     VECTOR.
C
      DIMENSION X1(1),X2(1),X3(1)
      GO TO(1,4,5),NOP
    1 S=1.
    2 DO 3 J=1,3
      X3(J)=X1(J)+S*X2(J)
    3 CONTINUE
      RETURN
    4 S=-1.
      GO TO 2
    5 DO 6 J=1,3
      K=J+1-3*(J/3)
      L=J+2-3*(J/2)
      X3(J)=X1(K)*X2(L)-X1(L)*X2(K)
    6 CONTINUE
      RETURN
      END
```

```
      SUPROUTINE POT(V1,V3,ARG,NAXIS)
C
C     THIS SUBROUTINE PERFORMS A TWO DIMENSIONAL ROTATION OF VECTOR V2
C     BY AN ANGLE ARG(RADIANS),WHICH IS NEGATIVE FOR CLOCKWISE
C     ROTATIONS AND POSITIVE FOR COUNTERCLOCKWISE ROTATIONS. V2 IS THE
C     ROTATED VECTOR. NAXIS IS THE AXIS OF ROTATION WHICH IS 1,2,OR
C     3 FOR ROTATIONS ABOUT THE X,Y OR Z AXIS RESPECTIVELY.
C
      DIMENSION V1(1),V2(3),V3(1)
      C=COS(ARG)
      S=SIN(ARG)
      I=NAXIS+1-3*(NAXIS/3)
      II=NAXIS+2-3*(NAXIS/2)
      V2(NAXIS)=V1(NAXIS)
      V2(I)=V1(I)*C+V1(II)*S
      V2(II)=-V1(I)*S+V1(II)*C
      V3(1)=V2(1)
      V3(2)=V2(2)
      V3(3)=V2(3)
      RETURN
      END
```

```
      SUBROUTINE JULDAY(JDAY,YEAR,MONTH,DAY)
C
C     JULIAN DAY FOR MONTH-DAY-YEAR IN 20TH CENTURY
C
C           WHERE YEAR = 00-99
C                 MONTH = 1-12
C                 DAY = 1-31
C
      DIMENSION MOSUM(12)
      INTEGER YEAR,MONTH,DAY,JDAY
      DATA MOSUM/0,31,59,90,120,151,181,212,243,273,304,334/
C
      LEAP = (YEAR - 1) / 4
      JDAY = 2415019 + 365*YEAR + LEAP + MOSUM(MONTH) + DAY
      IF (MOD(YEAR,4)) 1,2,1
    2 IF (YEAR) 3,1,3
    3 IF (MONTH - 2) 1,1,4
    4 JDAY = JDAY + 1
    1 RETURN
      END
```

```
      SUBROUTINE FPPOS(CC,SLRI,RHO,ACEN,DEC,DELTAE,
     1 GH,FL,XV,YV)
      DIMENSION CC(3),RHO(3,3),ACEN(3),DEC(3),DELTAE(3),GH(3),
     1 FL(3)
      DIMENSION TEMP1(3),TEMP2(3),TEMP3(3)
      IC=0
      IK=1
      PI=3.14159265358979
      I=1
      J=2
      CALL SCALCF(CC,TEMP1,SLRI,1)
      CALL VECTOR(TEMP1,RHO(1,I),TEMP1,1)
      AA=ASIN(TEMP1(3)/SQRT(TEMP1(1)**2+TEMP1(2)**2+TEMP1(3)**2))
      BB=ATAN2(TEMP1(2),TEMP1(1))
      CALL CONVRT(2,GLA,GLO,ATL,AA,BB,TEMP1)
      AC1=0.0
      AC2=0.0
      DO 1121 KI=1,3
      AC1=RHO(KI,J)**2+AC1
      AC2=TEMP1(KI)**2+AC2
 1121 CONTINUE
      CALL VECTOR(TEMP1,RHO(1,J),TEMP1,2)
      ROT=DELTAE(J)
      CALL RLNSGT(SIG,ETTA,ACEN(J),DEC(J),ROT,
     1GH(J),TEMP1(1),TEMP1(2),TEMP1(3))
      DD=FL(J)*TAN(SIG)
      IF(ETTA.GE.0.0.AND.ETTA.LE.PI/2.) GO TO 1122
      IF(ETTA.GE.PI/2.0.AND.ETTA.LE.PI) GO TO 1123
      IF(ETTA.LE.0.0.AND.ETTA.GE.-PI/2.) GO TO 1124
      ETTA=PI+ETTA
      TEMP2(IK)=-DD*COS(ETTA)
      TEMP3(IK)=-DD*SIN(ETTA)
      GO TO 21
 1122 TEMP2(IK)=DD*COS(ETTA)
      TEMP3(IK)=DD*SIN(ETTA)
      GO TO 21
 1124 ETTA=-ETTA
      TEMP2(IK)=DD*COS(ETTA)
      TEMP3(IK)=-DD*SIN(ETTA)
      GO TO 21
 1123 ETTA=PI-ETTA
      TEMP2(IK)=-DD*COS(ETTA)
      TEMP3(IK)=DD*SIN(ETTA)
   21 CONTINUE
      YV=TEMP3(1)
      XV=TEMP2(1)
      RETURN
      END
```

```
SUBROUTINE RLNSGT(SIGMA,ETA,ASCENC,DECLC,DELTAE,TAU,X,Y,Z)
DIMENSION V(3)
PI=3.14159265358979
V(1)=X
V(2)=Y
V(3)=Z
ANG=-TAU+ASCENC
CALL ROT(V,V,ANG,3)
ANG=PI/2.-DECLC
CALL ROT(V,V,ANG,2)
ANG=DELTAE
CALL ROT(V,V,ANG,3)
CALL SCALCF(V,V,XX,2)
XX=1./SQRT(XX)
CALL SCALCF(V,V,XX,1)
SIGMA=ACOS(V(3))
XX=SIN(SIGMA)
ETA=ATAN2(V(2),V(1))
RETURN
END
```